CFD SIMULATIONS OF CONTAMINANT TRANSPORT BETWEEN TWO BREATHING PERSONS

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ABSTRACT

Experiments have shown that exhalation from one person is able to penetrate the breathing zone of another person at a distance. Computational Fluid Dynamics (CFD) is used to investigate the dependency of the personal exposure on some physical parameters, namely: Pulmonary ventilation rate, convective heat output, exhalation temperature, and cross-sectional exhalation area. Full-scale experimental results are used to calibrate/validate the CFD model. Respiration, although an inherently transient phenomenon, is simulated by steady-state CFD with reasonably good results. Different geometries and grid distributions are tested to see what level of complexity is necessary. To further evaluate the experimental results, the CFD simulations are then used to perform parameter variations. The simulations show that the simulated personal exposure is very sensitive to variations in the convective heat output of both the exposed person and the exhaling person, and in the cross-sectional exhalation area and the pulmonary ventilation rate of the exhaling person.

KEYWORDS: Breathing zone, CFD, Contamination sources, Convection flows, Respiration

INTRODUCTION

A subject which has not yet been studied thoroughly is the dispersion of contaminants from the human exhalation, and the interaction taking place between respiration and the convective boundary layer flow induced by the human body. These phenomena are important when trying to understand and predict the flow fields and the resulting contaminant distributions in displacement ventilated rooms, and may also be interesting with respect to contaminant control in hospitals and clinics, in situations with passive smoking, and in the general improvement of indoor air quality. In the present study, focus is on situations where two persons are close to each other, so that the exhalation of one person can penetrate the breathing zone of another person.

Aims

The simulations presented in this paper are intended to complement a series of full scale experiments made in a displacement ventilated test room (Bjørn and Nielsen 1996). In these experiments, two breathing thermal manikins were used: manikin no.1 acted as contaminant source, breathing directly towards the face of manikin no.2. Tracer gas N_2O was added to the exhalation, and manikin no.2 was used for measuring personal exposure. Manikin no.1 exhaled through either nose or mouth, and different distances between the two manikins were tested. The main results of the measurements are shown together with simulated results in figures 8, 10 and 12 in this paper. The principal aim of these simulations is to assess the sensitivity of the physical situation to variations of different parameters. This will assist in the evaluation of the experimental results.

METHODS

The CFD code

A commercial CFD code named FLOVENT is used. The code uses a standard finite volume method, the k-ε turbulence model with logarithmic wall functions, rectangular structured grid, the hybrid discretisation scheme, and the SIMPLE solving algorithm, see Patankar (1980).

Geometry

The geometry of the test room and the experimental setup is symmetrical. For saving CPU time, only half of the room and half of the manikins are simulated, see figure 1. The symmetry plane is an adiabatic, frictionless wall.

To test the importance of the geometrical modelling of a human being, two different types of computer simulated persons (CSPs) are compared: 1) a simple box, and 2) a model with separate head, torso, and legs (see figure 2 and table 1). These two models have been used before by Brohus and Nielsen (1996), Brohus (1997). The surface area is 1.62 m^2. This is the surface area that is in contact with the ambient air. The area in contact with the floor is not included, and there is no heat conduction from the CSP to the floor.

The present CSPs differ from those used by Brohus and Nielsen (1996) by having a "mouth", which is used as an inlet for CSP no.1 and as an exhaust for CSP no.2, thus simulating the effect of exhalation and inhalation, respectively. The centre of the mouth is placed at the height of 1.5 m

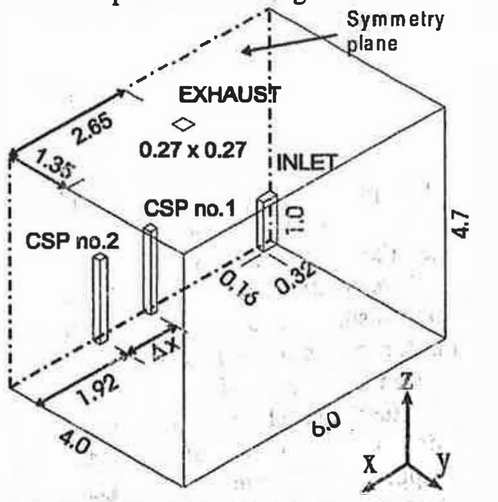

Figure 1: Geometry of test room, location of CSPs, inlet, and exhaust.

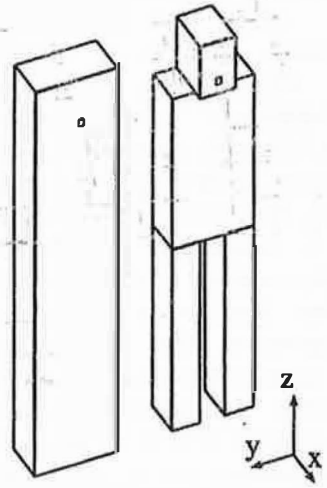

Figure 2: Simple and detailed CSP.

Table 1: Dimensions of Computer Simulated Persons in [m].

	Simple CSP			Detailed CSP		
Body part:	x	y	z	x	y	z
Torso	0.16216	0.3	1.7	0.14429	0.3	0.67
Leg	-	-	-	0.14429	0.105	0.8
Head	-	-	-	0.18	0.13	0.23
Mouth		0.0106	0.0106	-	0.0106	0.0106

Grid Size

The solution will change with grid size. The discretisation error is of the first order of cell size. Theoretically, the solution will move asymptotically towards a "grid independent" solution (being the analytical solution of the differential equations). It is however not possible to say beforehand exactly just how fine the grid should be, or how large the deviations will be. A systematic investigation into this problem is very time consuming, so it has only been dealt with for one situation. The results have then been used as a guideline for the rest of the situations. The distance to the first grid line is 1.0 cm from all surfaces. This is an appropriate distance with regard to the calculation of the convective heat transfer coefficient (Brohus (1997)).

Boundary conditions

Convective heat fluxes **Φ**, temperatures **T**, mass flow rates **m**, and contaminant concentrations **c** are prescribed (see table 2). Heat exchange by radiation is disregarded (since the flow is dominated by convection), and the convective heat output of the CSPs is assumed to be 50% of the total heat output of the manikins, excluding the exhalation. The constant flow rate and temperature of the exhalation is a simplification compared to reality, where the exhalation shows a pulsating, intermittent behaviour. The mass flow rate of 3.77×10^{-4} kg/s is the maximum instantaneous flow rate of a person breathing 6 liters pr. minute at a frequency of 10 breaths pr minute, assuming a sinusoidal variation of the flow rate.

Table 2: Boundary conditions

	External boundaries					CSP no1		CSP no.2	
	floor	ceiling	walls	inlet	exhaust	inlet	surface	exhaust	surface
Φ [W/m^2]	-	-	-	-	-	-	25	-	25
T [°C]	21.3	22.0	21.5	19.5	-	32	-	-	-
m [kg/s]	-	-	-	5.33e-2	5.33e-2	3.77e-4	-	3.77e-4	-
c [g/kg air]	-	-	-	0	-	7.9	-	-	-

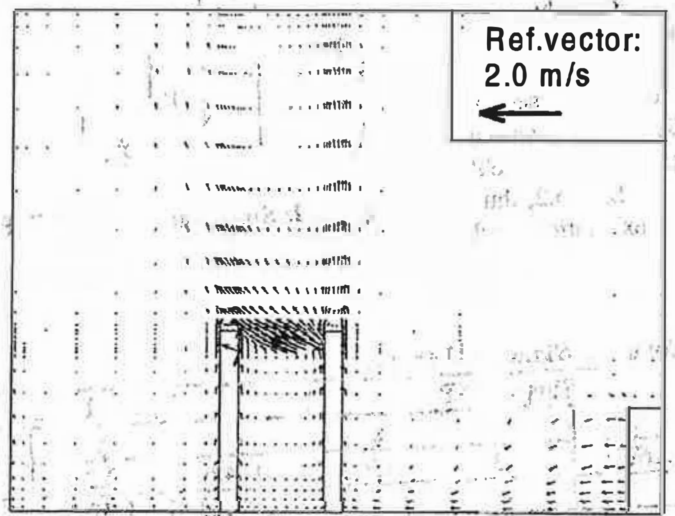

Figure 3: Velocity field, x-z plane, y = 0. Velocities > 1.0 m/s (close to the exhalation opening) are omitted

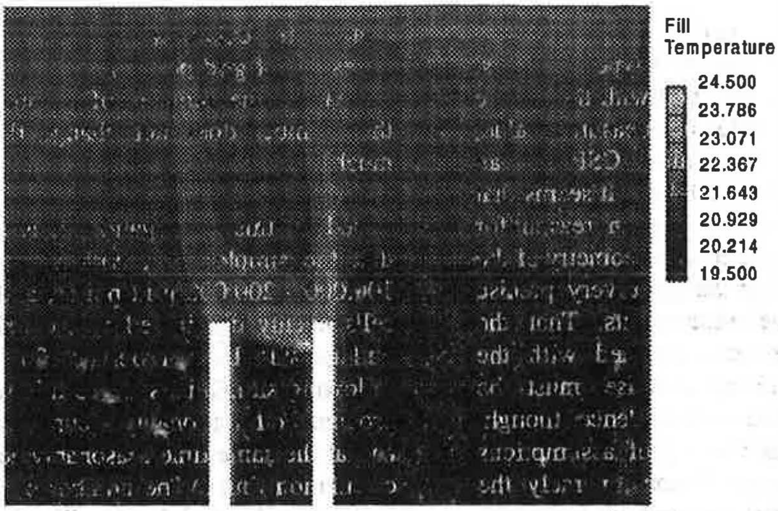

Figure 4: Temperature field, x-z plane, y = 0. Temperatures larger than 24.5°C appear as white.

RESULTS

In all simulations, physically realistic results are obtained (see example in figures 3 and 4), i.e. the flow is quite similar to reality. The simulated personal exposure, however, is very sensitive to details.

Grid independence

An investigation was made to assess the optimum number of grid points for the simulations. The investigations were limited to a situation with horizontal exhalation through the mouth of one CSP and a mutual distance $\Delta x = 0.4$ m.

The exposure c_e, i.e. the concentration inhaled by CSP no.2, is simulated. In the following the exposure is made dimensionless by dividing with the return concentration c_R. In the equivalent full-scale experiment, $c_e/c_R = 6.90$.

Figure 5 shows that we can not be completely sure that grid independence is reached, even for the rather large number of 400,000 grid points, but the results do seem to be reaching an asymptotical solution. However, when the number is below approx. 100,000 the results change dramatically.

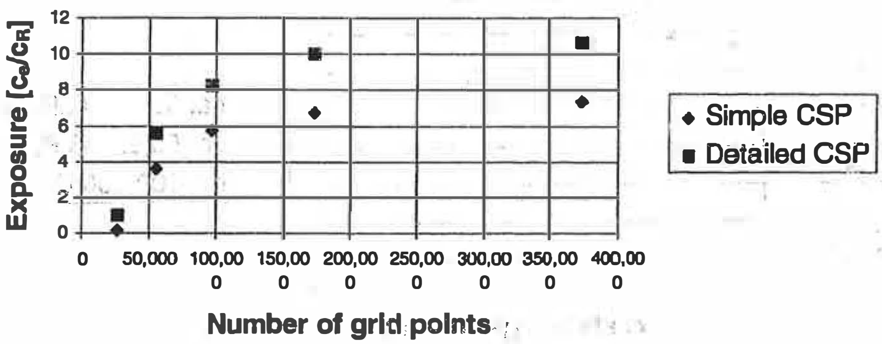

Figure 5: Investigation of grid point independence.

The above mentioned gridpoint investigation includes both types of CSPs. In fact, the result obtained with the simple CSP is very close to the measured value, whereas the more detailed CSP has an overshoot of approx. 30-40%. It seems that the geometry is not the main reason for deviations. The rectangular geometry of the detailed CSP is in fact not very precise compared to the experiments. That the simulated exposures obtanined with the simple CSP are so precise must be considered a bit of a coincidence, though, since there are a number of assumptions involved in the simulations, namely the lack of intermittent, pulsating breathing. The code itself also includes some inaccuracies (se the discussion later).

Core region

In the above calculations, grid points were concentrated in the area between the two CSPs, whereas they were more scarce in the areas around and above the CSPs (because of the structured rectangular grid distribution, however, there is a considerable waste of grid points). Apart from the density of gridpoints between the two CSPs, the grid density in the exhalation outlet proves to be importance, see figures 6 and 7. It is beneficial to use a high number of grid points in this region. For a given grid density, however, it seems that there exists a maximum number necessary of grid points in the core region. Increasing the number of points beyond this number does not change the result much.

Based on this investigation, it is assumed that the simple CSP, with a number of 100,000 - 200,000 grid points, and with 8 cells evenly distributed in the exhalation outlet, will be appropriate for all the following simulations, since this seems to produce both reasonably accurate solutions and at the same time reasonably economic calculation times. The number of 100,000 grid points is used for the distance of 0.4 m, at increasing distances the number of gridpoints in the x-direction between the two manikins is increased proportionally with the distance.

Parameter variations

1. Inhalation

Two simulations are made without air being extracted through the inhalation of CSP no. 2. The simulations are made for Δx = 0.4 m and 0.6 m, with exhalation through the mouth of CSP no 1. The simulated exposures are 2-3 times as large as with air being inhaled, proving that this is an important detail, at least in this type of situation. Inhalation is used in all other simulations.

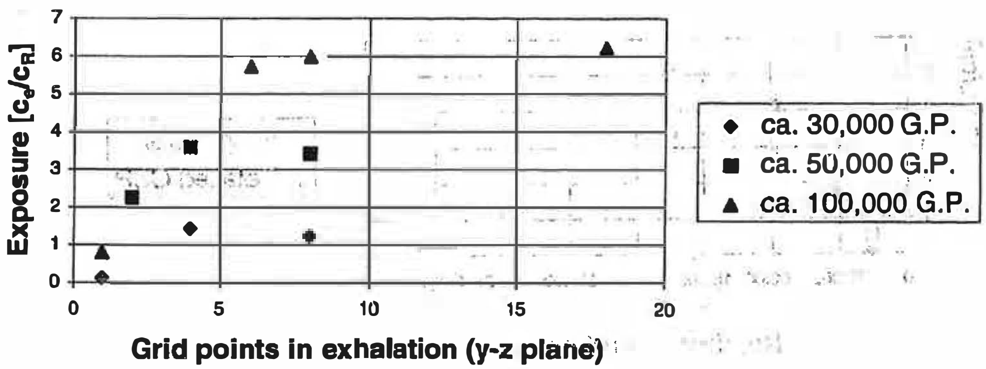

Figure 6: Dependence of grid points in core region

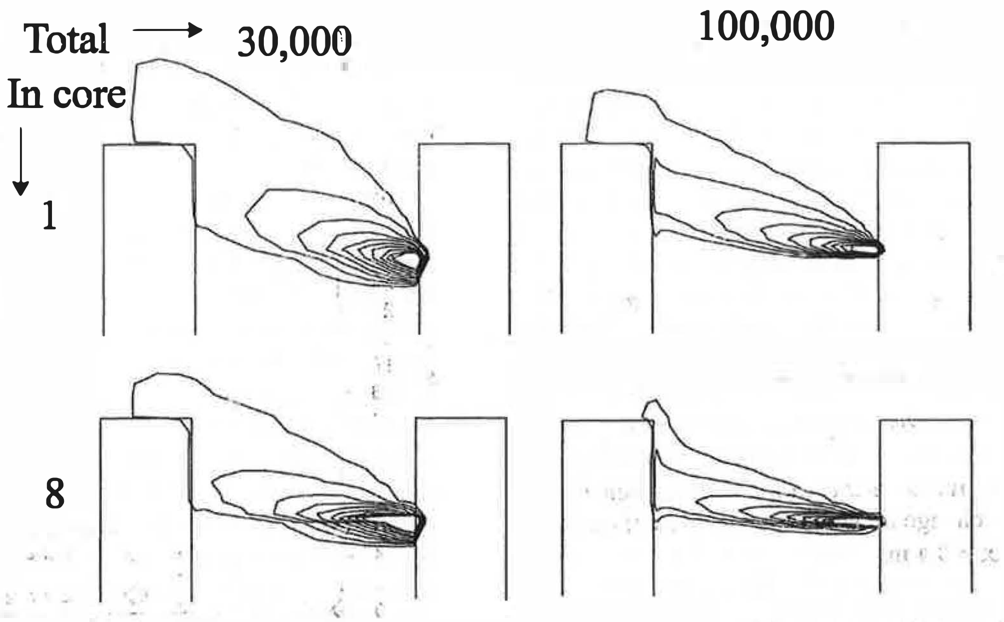

Figure 7: Development of exhalation jet with different grid distributions. Contour lines represent equal concentrations in all cases.

2. Excess temperature of exhalation
There is a slight difference (< 1 %) between the density of exhalation air in the experiments and in real life, which corresponds to a temperature difference of max. 3 °C. The results are tested for sensitivity towards changes in exhalation temperature, see figure 8. The results indicate that this parameter is of importance at distances > approx. 0.6 m.

3. Convective heat output
Since the boundary layer flows around persons interact with the exhalation flow, different convective heat outputs are tested, see figure 9. The effect of variations of this parameter is considerable. Without any heat at all, the simulated personal exposure $c_e/c_R \approx 15$, i.e. more than twice the measured value.

4. Mouth area of CSP no.1
The mouth area was doubled (twice as wide) in a series of experiments. This has a dramatic effect on the simulated exposure, which drops to 0.07 - 0.03 for the distances 0.4 - 1.0 m. When the flow rate is increased, however, the difference diminishes, see figure 11.

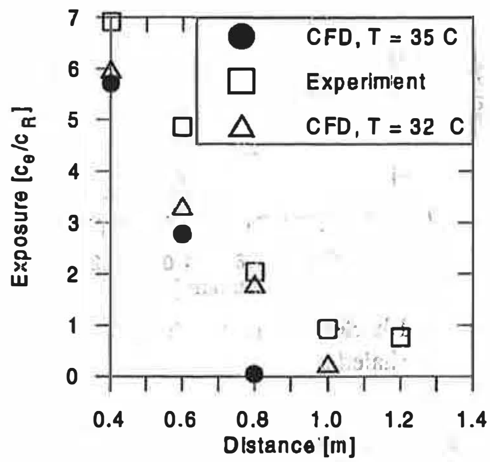

Figure 8: Simulated exposure, sensitivity to change in exalation temperature.

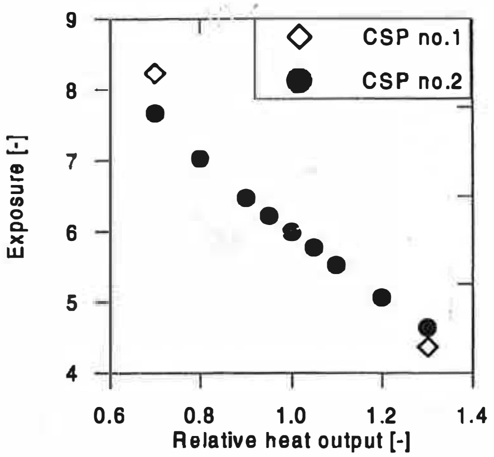

Figure 9: Simulated exposure, sensitivity to change in heat outputs, constant distance $\Delta x = 0.4$ m.

5. Pulmonary ventilation rate

When the flow rate of the air exhaled by CSP no.1 is inceased, a significant change is seen in the simulated esposure, see figures 10 and 11.

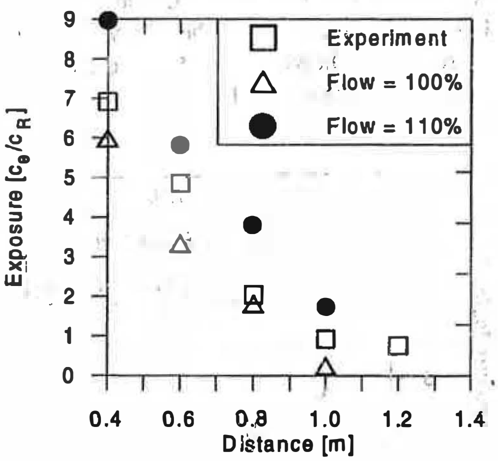

Figure 10: Sensitivity to change in flow rate of exhaled air.

6. Nose exhalation

When simulating air exhaled through the nose, the mouth was made double as wide, and the exhalation was forced to leave the opening with a 45° downward inclination and a 15° horizontal inclination, corresponding to the experiments. This produces rather poor results for distances larger than 0.4 m, see figure 12. The simulations in this situation had some convergence problems, and no further simulations were attempted.

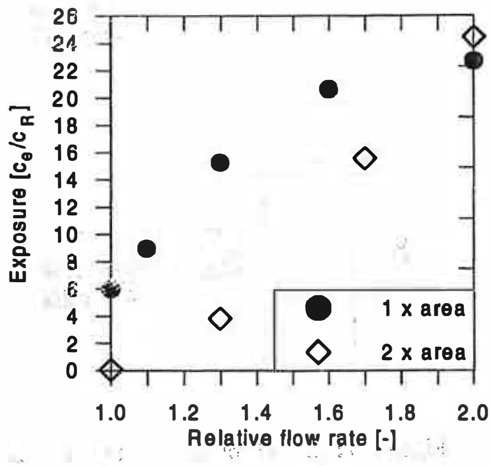

Figure 11: Sensitivity to changes in flow rate, constant distance $\Delta x = 0.4$ m.

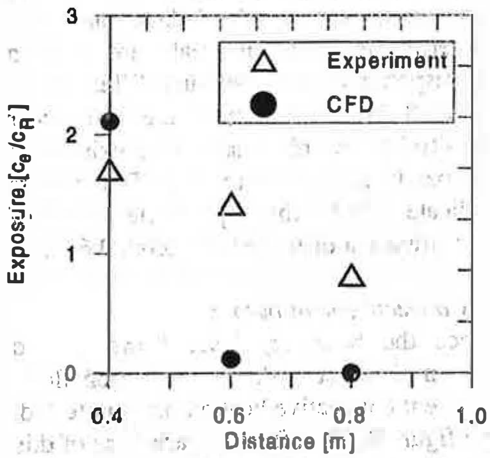

Figure 12: Exhalation through nose

DISCUSSION

Several aspects of the simulations do not correspond well to reality. Logarithmic wall functions are used, however, this will give poor predictions of the flow in areas with low local Reynolds numbers, e.g. in the lower parts of the boundary layer flow close to the human body. It might be better to use a low Reynolds model, but this was not possible for practical reasons (CPU time). The same problem arises with the steady-state assumption: It would be better to use transient calculations, but again, this would demand an increase in CPU time beyond what was possible. Also, the k-ε turbulence model does not resolve the turbulent eddies in the flow, which might be of importance when considering contaminant exposure. The geometries in the simulations are much simpler than reality. It might be better to have body fitted grids, but the FLOVENT code does not support this feature.

In spite of the principal limitations of the present simulations, it was possible to simulate results which are physically realistic, although not completely accurate when compared with full-scale measurements. For this reason, it is concluded that the simulations are adequate for testing sensitivity to certain parameter variations, which was the main objective of this research. The grid distribution is paramount; an inadequate number of grid points will have a severe influence on the accuracy of the results. This is a problem in all CFD work which is sometimes neglected, probably because it is so time consuming.

The simulations show that the simulated personal exposure is very sensitive to variations of the investigated parameters:

- convective heat outputs
- cross-sectional exhalation area
- pulmonary ventilation rate.

Furthermore, the results indicate that the simulated exposure is not very sensitive to variations of exhalation temperature at small mutual distances, but more so as the distance increases. However, since only a narrow range of temperatures are relevant to this problem, this parameter (and other parameters influencing the density of the exhaled air (as e.g. humidity and CO_2 content) can be considered as less critical.

The results suggest that one should not focus so much on the exact measured values when evaluating the practical importance of the experiments, but rather look at the qualitative aspects, namely that the exhalation does not necessarily follow the convective flows close to the body, but is able to penetrate the breathing zone of other persons located nearby.

It would have been interesting to look at the effect of breathing towards the side or back of another person at different angles and with varying vertical and horizontal inclination of the exhalation jet, but it is deemed that the computational model is not ideal for this type of problem, considering the problems encountered in simulating exhalation through the nose.

REFERENCES

E.Bjørn, P.V.Nielsen (1996). "Exposure due to Interacting Air Flows between Persons."*Proc. ROOMVENT '96, 5th Int. Conf. on Air Distribution in Rooms*, Yokohama, Japan. Vol.1, pp.107-114.

H.Brohus, P.V.Nielsen (1996). "CFD Models of Persons Evaluated by Full-Scale Wind Channel Experiments." *Proc. ROOMVENT '96, 5th Int. Conf. on Air Distribution in Rooms*, Yokohama, Japan. Vol.2. pp 137-144.

H.Brohus (1997). "Personal Exposure to Contaminant Sources in Ventilated Rooms." Ph.D. Thesis, Aalborg University, Denmark.

S.V.Patankar (1980). "Numerical Heat Transfer and Fluid Flow." Hemisphere